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INTERACTIONS BETWEEN SATELLITES AND PLASMA

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16. Abstract

The interactions of a spacecraft with the surrounding streaming plasma are determined by the following effects: the fade-out of the plasma in the wake of the probe, the emission of the photoelectrons and secondary electrons, the differential charging of the surface of the probe and a spatial potential distribution in the vicinity of the space probe. These effects and their importance are discussed with consideration of the following plasma conditions: 1) geostationary satellite orbits, 2) in the solar wind (HELIOS mission), and 3) in the ionosphere at an altitude of 250 km (the projected OSV on Spacelab). A review of the fundamental models is given based on the kinetic theory of plasma (Vlasov-Maxwell system).

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INTERACTIONS BETWEEN SATELLITES AND PLASMA

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1. Introduction /305*

A real problem arises in the measurement of plasma from satellites: the surrounding plasma is disturbed by the satellite itself and its surface is electrically charged. For the evaluation of the plasma measurements, the satellite's potential and the disturbance must be known in order to be able to determine the undisturbed plasma. Corresponding to the schematic presentation in Fig. 1, space charges around the satellites are produced by the following effects:

a) The relative streaming plasma is faded-out by the satellites. Due to their very high thermal speed, the electrons refill the wake very strongly, so that an extensive negative space charge is formed.

b) Photoelectrons, which can form a cloud of negative space charges in front of the satellite, are emitted from the parts of the probe's surface which are irradiated by the /306
Sun.

c) Secondary electrons can be emitted by the reflection of high energy plasma particles.

d) Plasma electrons are backscattered on the probe's surface. The spectrum of the backscattered electrons contains both elastic and inelastic stray components.

These interactions cannot be experimentally simulated in plasma chambers. Even the chamber's walls would emit secondary

*Numbers in the margin indicate pagination in the foreign text.

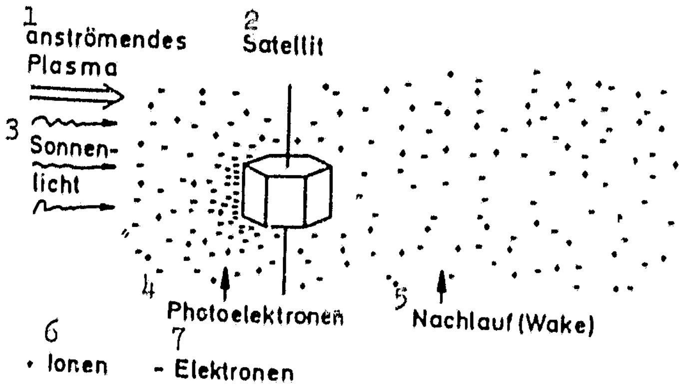

Fig. 1. A schematic representation of the space charges around a satellite.

Key: 1. Streaming plasma; 2. Satellite; 3. Sunlight; 4. Photoelectrons; 5. Wake; 6. Ions; 7. Electrons.

electrons and backscatter the plasma electrons -- to a much greater degree than the small simulation probe itself. Furthermore, the necessary thermal isotropy and homogeneity of the plasma's electron components cannot be attained.

The surface is electrically charged by the plasma stream on the probe and by the streams of photo- and secondary electrons moving away from the probe. The floating potential is obtained from the flux balance (the disappearance of the joint stream). The knowledge of this floating potential is, for example, necessary for the interpretation of the measured electron spectrum in the HELIOS mission. The properties of the surface material are included in the flux balance, which for different parts of the surface results in the general differential potential (differential charging). Potential differences of around 10 kV between the satellite's various parts can be obtained for geostationary satellites, which has already led to electronic failures in the satellite. The SCATHA (Spacecraft Charging at High Altitude) program of the USAF should experimentally study these charging effects.

Space plasma is very homogeneous in comparison to that in a plasma chamber, so that it is especially suitable for the study of wave phenomena. The potential distribution around the probe, which is induced by the undisturbed plasma, can stimulate the waves themselves (instabilities). There is, however, only little information available about this type of instability taking into consideration the magnetic field.

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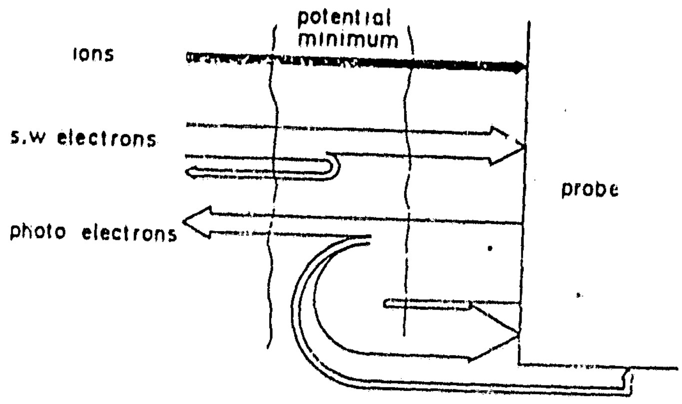

Fig. 2. A schematic representation of the flux balance on an element of the probe's surface for plasma conditions in a solar wind. The scattering of the photoelectrons on the other parts of the satellite's surface is essential. The potential minimum in front of the probe represented here is obtained only in a solar wind, in other cases different surface potentials cause a similar effect.

The need, therefore, arises to investigate the interaction of satellites with space plasma in order to reach the first level of a universal probe theory valid under conditions of outer space. If the plasma in a strongly disturbed region is not in thermal balance (great free path), the necessary theoretical treatment can ensue only on the basis of the statistical kinetic theory.

2. Basic Equations

2.1. The Vlasov-Poisson System

The following approximations are accomplished very well for all of the plasma conditions discussed in this article:

a) The interactions between satellites and plasma should be stationary. The possible stimulation of instabilities can be ignored.

b) The plasma can be treated in a very good approximation as smooth (Vlasov plasma).

c) The influence of the magnetic field can be ignored because of the very large gyro radii relative to the satellite's characteristic dimensions. This supposition is only conditionally valid for the ionospheric conditions.

Consequently, the interaction of the satellite with the surrounding plasma is to be described by the Vlasov-Poisson system: /307

The Vlasov formula:

$$\underline{v}\cdot\nabla_x f_\mu(\underline{x},\underline{v}) - \frac{q_\mu}{m_\mu}\nabla_x\phi(\underline{x})\cdot\nabla_v f_\mu(\underline{x},\underline{v}) = 0 \tag{1}$$

for $\mu = i$, e the plasma particle types

The Poisson formula:

$$\Delta\phi(\underline{x}) = -\frac{4}{\varepsilon_0}\sum_{\mu=i,e} q_\mu \iiint_{-\infty}^{\infty} f_\mu(\underline{x},\underline{v})\, d^3v \tag{2}$$

The flux balance formula:

$$\underline{j}(\underline{x}=\underline{x}_s) = \sum_{\mu=i,e} q_\mu \iiint_{-\infty}^{\infty} \underline{v}\, f_\mu(\underline{x},\underline{v})\, d^3v \tag{3}$$

with $\underline{x}_s$ on the probe's surface;

$$j_n(\underline{x}_s) = 0$$

The flux's normal component disappears for a surface element $\underline{x}_s$ with insulated material.

$$\sum_\alpha \iint_{F_s^\alpha} \underline{j}(\underline{x}_s)\cdot d\underline{F} = 0$$

The total flux on all the conductive surface parts F_s (which are electrically connected) disappears. An electrical model of the satellite is necessary here (with a time-dependent spin).

The formulas contain the following symbols:

$\underline{x}$, $\underline{v}$	location and velocity coordinates
q_μ, m_μ	charge and mass of the μ-type particles (μ = i, e)
$f_\mu(\underline{x}, \underline{v})$	distribution function in the 6-dimensional phase space
$\Phi(\underline{x})$	electrical potential
$\underline{j}(\underline{x})$	electrical current density

The following limit conditions are valid for a definite solution of the Vlasov-Poisson system:

$$f_i(\underline{x},\ \underline{v}) = 0 \text{ with } \underline{v}\cdot\underline{n} \geq 0$$

All the ions should be neutralized on the surface.

$$f_e(\underline{x}_s,\underline{v}) = f_e^{Ph}(\underline{x}_s,\underline{v}) + f_e^{sec}(\underline{x}_s,\underline{v}) + f_e^{scat}(\underline{x}_s,\underline{v}) \text{ with } \underline{v}\cdot\underline{n} \geq 0$$

Photo Secondary backscattered electrons

$$(f_e^{Ph}(\underline{x}_s,\underline{v}) = 0 \text{ if } \underline{x}_s \text{ is shaded})$$

$$\lim_{|\underline{x}|\to\infty} f_\mu(\underline{x},\underline{v}) = f_\mu^\infty(\underline{v})$$

in general for electrons isotropic Maxwell distribution, for ions, Maxwell distribution shifted by the relative velocity;

$$\lim_{|\underline{x}|\to\infty} \phi(\underline{x}) = 0$$

The other boundary condition for the potential ϕ on the probe $\phi(\underline{x}_s) = \phi_s(\underline{x}_s)$ must be determined from the flux balance equation (3).

This Vlasov-Poisson system with boundary conditions can be solved with the characteristic methods: the distribution function $f_\mu(\underline{x},\ \underline{v})$ is constant in a particle's orbit (a characteristic of the Vlasov formula). The distribution function can be determined by orbital tracking up to the limit value. The combined particles (trapped particle orbits) can be ignored here. /308

2.2. Iteration of the Vlasov-Poisson System

A general solution technique of the integration of the Vlasov-Poisson system will be presented below in order to clarify the causal relationship of the system and of the limit value. An appropriate selection of the initial potential $\phi^o(\underline{x})$ is presumed, the upper index indicates the corresponding stage of the iteration.

Potential $\phi^k(\underline{x})$

1. The calculation of the distribution function $f_\mu^k(\underline{x},\ \underline{v})$ in the potential $\phi^k(\underline{x})$ is carried out by the particle orbit tracking up to the limit value on the probe's surface or in the undisturbed plasma.

(In general, the distribution function for the electrons emerging on the probe's surface is dependent on the distribution of the arising particles (secondary electrons and backscattering), so that the distribution function of the emerging electrons must first be calculated by a further iteration.)

2a. The particle density $n_{\mu}^{k}(\underline{x})$ is calculated by integration over all the possible orbits:

$$n_{\mu}^{k}(\underline{x}) = \iiint_{-\infty}^{\infty} f_{\mu}^{k}(\underline{x},\underline{v})\, d^{3}v$$

2b. The streams on the satellite's surface are calculated: From the flux balance (3), then follows the boundary condition for the potential on the surface $\underline{x}_s$: $\phi^{k+1}(\underline{x}_s)$. The parts of the probe's surface are the capacities against each other and against the undisturbed plasma).

3. The solution of the Poisson formula (2): from this results the potential or the next iteration step

$$\text{Potential } \phi^{k+1}(\underline{x}$$

In general this iteration procedure is convergent. The self-consistent potential and density distributions obtained thus are then the solutions of the Vlasov-Poisson system (1-3). Calculations of this type have been performed numerically with great simplifications (for example, by I. Katz et al., 1977, and L.W. Parker, 1977).

2.3. Numerical Plasma Simulation

A completely different solution procedure is numerical plasma simulation, in which the motion equation of very many particles is simultaneously solved (for example, by Isensee, 1977). The plasma particles are represented as discrete particles of very great mass and charge because of the numerical capacity restriction according to the particle-in-cell method (Morse, 1970). This is performed on the outer limit of the simulation region

and on the probe's surface which corresponds to the boundary value of the distribution function. This simulation particle moves for a long period of time in the potential, which is then calculated anew through the tabulation of the particle densities and the solution of Poisson equation (2). Each simulation particle is observed until its orbit either leaves the simulation region or reaches the probe's surface and contributes to the flux balance. The floating potential is thus regulated so that the common stream on an element of the surface disappears. The simulation is performed until the potential no longer changes substantially. Statistical fluctuations in the particle densities and the potentials result from the small number of simulation particles (around 10^4). /309
Another numerical problem is the very small spatial resolution near the probe's surface (see also L.W. Parker, 1977). In this form the numerical plasma simulation is only possible if, on the one hand, the simulation region is several Debye lengths long, and, on the other hand, a sufficient number of simulation particles are inside a Debye sphere -- this is accomplished directly with the plasma conditions of solar winds (see Section 3.2). The stationary potential and density distributions are then the self-consistent solutions of the Vlasov-Poisson system.

3. Models Under Different Plasma Conditions

3.1. Plasma Conditions

The table on the following page cites the typical plasma parameters for the conditions in solar winds, for geostationary orbit and in the ionosphere, respectively.

A highly thermal plasma with very slight density is in a /310
geostationary orbit; in the ionosphere it is cold, but very dense. In solar winds somewhat more moderate conditions are encountered. Apart from the electrical components the effect of the magnetic field is negligible in the ionosphere.

TABLE 1. THE TYPICAL PLASMA CONDITIONS FOR A SOLAR WIND, GEOSTATIONARY ORBIT AND MIDDLE IONOSPHERE (PER DAY).

Plasma parameter:		Solar Wind 0.3 - 1.0	Geostationary Orbit (6.6 R_E)	Ionosphere 250 km
Thermal energy	kT_e	10 - 30 eV	3 - 30 keV	0.2 eV
	kT_i	10 - 20 eV	5 - 50 keV	0.1 eV
Plasma density n_o:		10 - 300 cm^{-3}	0.2 - 5 cm^{-3}	$2 \cdot 10^5$ cm^{-3}
Relative velocity of plasma to probe:	v_R	500 km/sec	30 km/sec	7 - 8 km/sec
Power numbers	$S_{e,i}$: $S_\mu = v_R/v_{th\mu}$	$S_e \ll 1 \ll S_i$	$S_e \ll S_i \ll 1$	$S_e \ll 1 \ll S_i$
Debye length (L_{sat}: Probe dimensions)	λ_D	$\lambda_D \sim L_{sat}$	$\lambda_D \gg L_{sat}$	$\lambda_D \ll L_{sat}$
Effect of magnetic field (r_G: Gyro radius)		$r_G \gg L_{sat}$	$r_G \gg L_{sat}$	$r_{Gi} \gtrsim L_{sat}$ $r_{Ge} \ll L_{sat}$
Photoelectrons	kT_{Ph}	1 - 3 eV	1 - 3 eV	1 - 3 eV
	n_{Ph}	$10^3 - 10^4$ cm^{-3}	$10^3 - 10^4$ cm^{-3}	$10^3 - 10^4$ cm^{-3}

3.2. Solar Winds

With the aid of numerical plasma simulations the potential distributions and the densities around a two-dimensional model probe (corresponding to the HELIOS satellites) were calculated by Isensee (1977 and 1978). In Fig. 4, the extensive negative potential structure can be seen through the fade-out of the solar winds' protons in the wake of the probe. A negative potential barrier, which is caused by the very dense photoelectric clouds, is found in front of the probe. All the electrons are presented in Fig. 3, while only the photoelectrons are in Fig. 5. The solar wind electrons, although faded-out by the probe, are only a little disturbed by the potential. They, like the protons, form a constant background. Secondary electron emission and backscattering are negligible under these plasma conditions. In front of the illuminated parts of the surface (the Sun shines from the left), the photoelectron density is very great and the

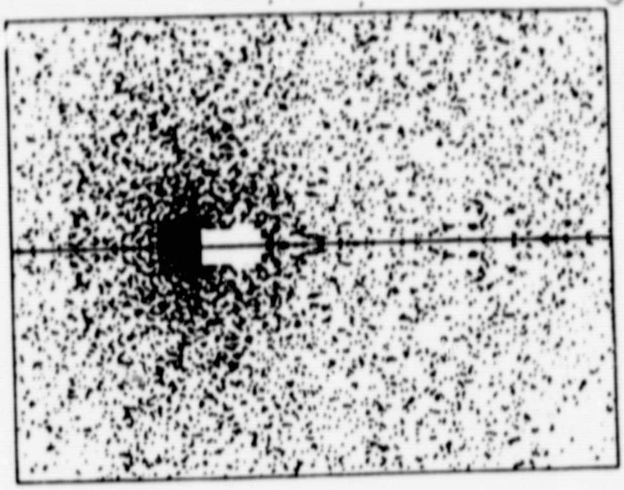

Fig. 3. The simulation particle in the numerical plasma simulation for a rectangular probe model with plasma conditions corresponding to those of a solar wind. Only the electrons are represented here. Left in front of the probe is the dense photoelectron cloud corresponding to Figs. 4 and 5. The Sun shines from the left (2-dimensional simulation model according to Isensee, 1978). The distance from the Sun: R = 0.3 AU.

inserted line corresponds to the position of the half-disturbed plasma density. The photoelectrons are scattered on the potential in the wake and cannot penetrate it.

The solar winds' protons are only negligibly disturbed by the probe. Because $|e\phi| << kT_1 << E_1^{kin}$ (E_1^{kin} = proton slip energy), the ion density behind the probe can be described by the neutron approximation. On the other hand, $E_e^{kin} << |e\phi| << kT_e$ is valid; a local Boltzmann distribution with geometric fade-out by the probe can therefore be taken as a good approximation of the solution of the Vlasov equation (1) for the solar wind electrons. Therefore the Vlasov equation (1) must still be solved only for the exiting photoelectrons: this is certainly not possible due to the strong nonlinear aspect of the Vlasov-Poisson system for realistic conditions.

For the wake, where the photoelectron density does not play an important role (Debye lengths in the probe's dimensions), the potential cah, however, be analytically calculated (Fig. 6). For shorter distances from the Sun, the wake's structure is significantly more pronounced. The floating potential in Fig. 6 stems from a spherically symmetrical (analytical) photoelectron model (Maassberg, 1978b). Here, because of the symmetry of the

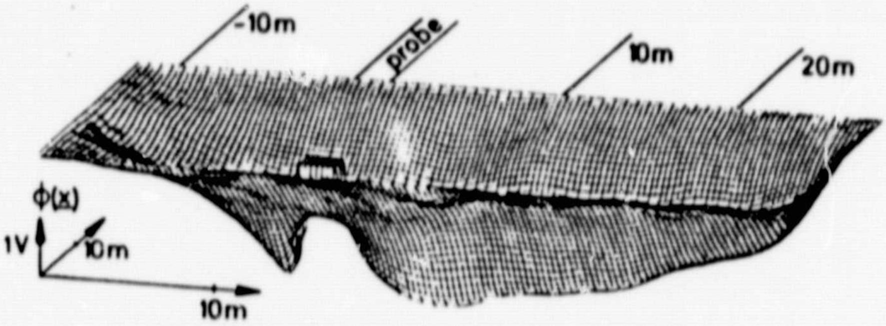

Fig. 4. The potential in the vicinity of a two-dimensional model probe in a perspective representation ($w_o \triangleq$ slip velocity of the solar wind, plasma parameter at around 0.3 AU. According to Isensee, 1978). Analogous to Figs. 3 and 5.

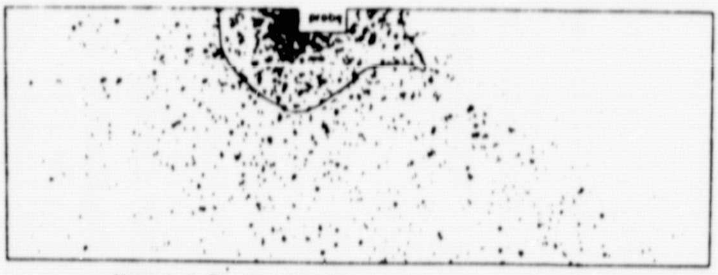

Fig. 5. Numerical plasma simulation. Photoelectrons in the vicinity of a probe in a solar wind (analogous to Figs. 3 and 4).

Vlasov-Poisson system, (1) and (2) and the flux balance equation can be approximated.

Under the conditions of a solar wind, the strong nonlinear character of the Vlasov-Poisson system is the main difficulty for describing the interactions of a probe with the surrounding plasma. Model calculations of this kind are necessary for interpreting the electron spectra, which are partially strongly disturbed by the potential near the probe, measured by the HELIOS mission.

3.3. Geostationary Orbit

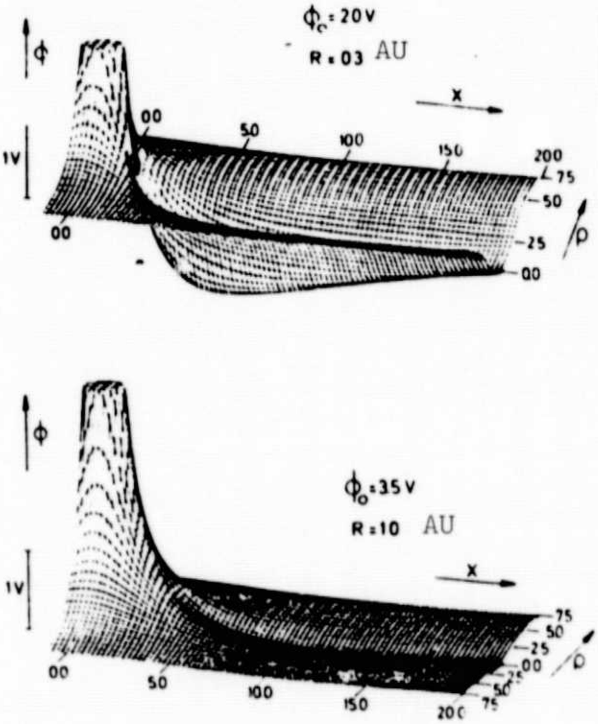

Fig. 6. A perspective representation of the potential in the wake of a sphere (radius 1.2 m) with plasma conditions for R = 0.3 AU (above) and R = 1 AU (below) according to Maassberg, 1978a.

The plasma in this region (radiation belt) has a much higher temperature than in a solar wind, but a lower density. The essentially greater electron flux negatively charges the probe's surface quite strongly, so that no photoelectron cloud can be formed in front of the probe. Since according to Table 1 the Debye length is very large in comparison with the characteristic dimensions of the probe, all of the space charges vis-a-vis the surface can be ignored. The floating potential is practically unshielded. Consequently, instead of the Poisson equation (2) only the Laplace equation must be solved for the potential: $\Delta\phi(\underline{x}) = 0$. In order to calculate the floating potential as the boundary value, the flux balance equation (3) must be integrated self-consistently with both the Vlasov equations (1). Photoelectrons, secondary electrons and backscattering near the plasma stream on the surface determine the potential structure around the probe. These streams are self-consistently calculated by Katz et al. (1977) for different parts of the surface by orbital tracking according to the iteration process in Section 2.2. Certainly the secondary electron emission and backscattering are not taken into consideration. According to the model calculations

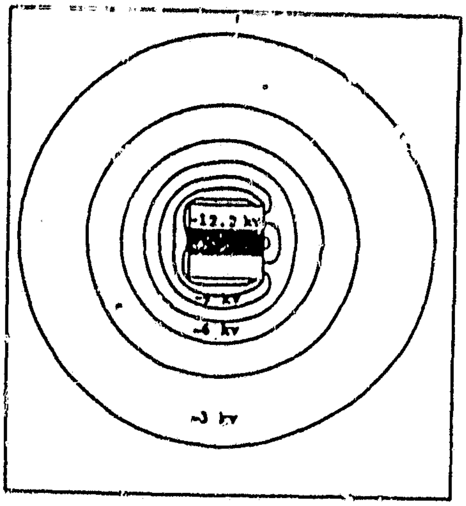

Fig. 7. Equipotential lines around a model satellite with conductive (cross-hatched) and nonconductive surfaces. The Sun shines from the right. (According to Katz et al., 1977.)

of Prokopenko and Laframboise (1977), however, these effects must be considered.

The potential distribution around a square block with different surface materials is presented in Fig. 7. The cross-hatched region represents metal, the rest should be covered with a dielectric film (solar cells). Since the potential like that of a monopole in the center of the model probe is related to the distance from the surface, the effect of the different surface potentials subsides. Potential differences of several kV appear, however, on the surface, the photoelectrons cause a somewhat higher potential on the illuminated, insulated parts of the surface. The chief problem under these conditions is the self-consistent solution of the Vlasov-Laplace system in connection with the flux balance equation for the individual parts of the satellite's surface with different materials. The properties of the materials with regard to the work function and photo- and secondary electron spectra have been recently investigated (for example, Prokopenko and Laframboise, 1977). /312

3.4. The Ionosphere

The ionosphere is represented fully contrary to the plasma conditions for a geostationary orbit: high plasma density and low temperatures. The Debye length is very short in comparison with the probe's characteristic dimensions, so that the floating potential is very quickly shielded. The photo- and secondary electron emissions as well as the backscattering are negligible because of the high density and low temperatures. The thermal velocity of the plasma electrons is very great in comparison with the slip velocity of the ions; the surface is hence electrically charged quite negatively, so that only a very small part of the electrons reach the probe. Furthermore, the electrons' gyro-radius is very small relative to the probe's characteristic dimensions (adiabatic motion of the electrons along the line of the magnetic field in the region of the probe). Therefore, the electron fade-out by the probe relative to the density is negligible. The potentials around the probe are negative everywhere, therefore the electron density can be approximated very well by a Boltzmann factor: $n_e(\underline{x}) = n_o \exp(e\phi(\underline{x})/kT_e)$. The Vlasov equation (1) for the electrons need not be solved any longer. For smaller probes (<1.0 m) the influence of the magnetic field on the ions' motion can also be ignored, with the plasma experiment planned within the framework of the OSV (Orbital Flux Experimental Station on the Spacelab) the probe to be measured is in this range. With the exception of the region directly behind the probe (a much closer wake), the condition of quasineutrality can be taken because of the very small Debye length in relation to the probe's dimensions and therefore also in relation to the characteristic changes of the potential in the wake: $n_e(\underline{x}) = n_i(\underline{x})$. Therefore in order to describe the wake structure under conditions of the ionosphere only the Vlasove equation (1) can be solved for the ions. The electron density is approximated by a Boltzmann factor and the Poisson equation (2) is solved by the conditions of quasineutrality. The floating potential has no influence on the wake structure.

3.5. The Influence of Surface Materials /312

In the previously described models, the interaction of the plasma with a satellite relative to the potential distribution in the plasma has stood in the foreground. In the following section a simulation model, following Soop (1972), is presented in which the external plasma is ignored (for example in the solar wind at the far outer half of the Earth's orbit). Photoelectrons, which return to the probe because of the surface's positive potential (the energy spectrum of the photoelectrons must be restricted to the top), are emitted from the probe's surface. The photoelectron clouds in front of the surface are shown in Fig. 8. The parts of the surface lying in the shadow (the picture on the right) have a small potential also on the front side in the sunlight, so that the photoelectron clouds are concentrated more in front of the illuminated parts. In the case of the conductive surfaces (left), the total probe is surrounded by photoelectrons, whose density in front of the illuminated parts of the surface is only somewhat larger.

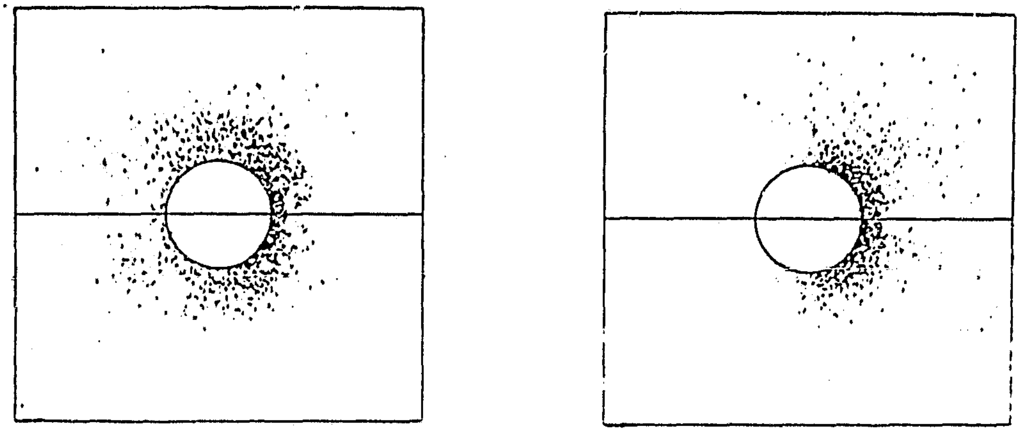

Fig. 8. The photoelectron clouds in front of a sphere ignoring the surrounding plasma. In the left picture is a conductive surface, in the right, an insulating one is simulated. The Sun shines from the right. Numerical plasma simulation according to Soop (1972).

The surfaces of real satellites consist of both conductive and non-conductive materials (solar cells). The charging effect and the potential structure around the satellite are, therefore, very complex and only barely comprehensible with the models used heretofore. The future direction of work in the field of probe theory in outer space conditions will depend on the information obtained from satellite measurements (plasma spectra) being understood on the basis of the models discussed here and the development of more realistic models. Similarly the results to be expected from the SCATHA program of the USAF are of special significance for the direction of modeling in the field of geostationary orbits and the plasma experiments planned within the framework of OSV on the Spacelab for the calculation of the wake structure under conditions of the ionosphere.

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